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Habitability of Planets in Binaries

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Abstract. A survey of currently known extrasolar planets indicates that close to 20% of their hosting stars are members of binary systems. While the majority of these binaries are wide (i.e., with separations between 250 and 6500 AU), the detection of Jovian-type planets in the three binaries of γ Cephei (separation of 18.5 AU), GL 86 (separation of 21 AU), and HD 41004 (separation of 23 AU) have brought to the forefront questions on the formation of giant planets and the possibility of the existence of smaller bodies in moderately close binary star systems. This paper discusses the late stage of the formation of habitable planets in binary systems that host Jovian-type bodies, and reviews the effects of the binary companion on the formation of Earth-like planets in the system's habitable zone. The results of a large survey of the parameter-space of binary-planetary systems in search of regions where habitable planets can form and have long-term stable orbits are also presented.

1. Introduction

Among the currently known planet-hosting stars, approximately 20% are members of binary systems (Haghighipour 2006). Although to observers, the existence of such *binary-planetary* systems is not unexpected¹, to theorists, such *extreme* planetary environments pose major challenges to theories of planet formation. While observations of systems such as L1551 (Rodriguez et al. 1998) indicate that planet-forming circumstellar disks, with masses similar to the mass of the primordial nebula of our solar system, exist around the components of binaries (implying that planet-formation in dual-star systems can begin and proceed in the same fashion as around our Sun), simulations of the formation of giant planets around stars of a binary yield mixed results. For instance, as shown by Nelson (2000), giant planets cannot form in binary systems with separations of ~ 50 AU through disk instability or core accretion mechanisms. However, as shown by Boss (2006) and by Mayer, Boss & Nelson (2007), disk instability can indeed form giant planets in binary systems, and as indicated by Thébault et al. (2004), the core-accretion mechanism is also capable of form-

¹Observations of star-forming regions have indicated that a large fraction of main and pre-main sequence stars are formed in dual or multistar environments (Abt 1979; Duquennoy & Mayor 1991; Mathieu 1994; Mathieu et al. 2000; White & Ghez 2001). There is also substantial evidence on the existence of planet-forming disks around stellar components of binary systems (Mathieu 1994; Akeson, Koerner & Jensen 1998; Rodriguez et al. 1998; White et al. 1999; Silbert et al. 2000; Mathieu et al. 2000).

ing planets in dual-star systems [see Haghighipour (2007) for a comprehensive review].

The fact that giant planets exist in binary systems implies that planet formation in dual-star environments is robust. One important concern with such systems is, then, whether they can also form and harbor habitable planets. In this paper, we study habitable planet formation in binary systems that are moderately close (i.e., separation smaller than 50 AU), and also harbor giant planets. Among the currently known binary-planetary systems only three are of this kind: GL 86 (Els et al. 2001), γ Cephei (Hatzes et al. 2003), and HD 41004 (Zucker et al. 2004; Raghavan et al. 2006). We are in particular interested to understand how the dynamics of the secondary star affects the late stage of the formation of terrestrial-class planets in the habitable zone of the primary and the delivery of water to its habitable planets.

2. Numerical Simulations

To study the late stage of habitable planet formation, the collisional growth of a few hundred Moon- to Mars-sized objects (planetary embryos) has to be simulated. In a recent article (Haghighipour & Raymond 2007), we carried out such simulations for a binary-planetary system with a solar-type star as its primary, a Jupiter-sized object at 5 AU as its planetary companion, and a 0.5-1.5 solar-masses star as its secondary. In these simulations, we assumed that planetesimal formation has been efficient and has resulted in the formation of a disk of approximately 115 planetary embryos with masses ranging from 0.01 to 0.1 Earth-masses. We randomly distributed these objects between 0.5 AU and 4 AU by 3 to 6 mutual Hill radii, and considered the increase in their masses with their semimajor axes (a) and the number of their mutual Hill radii (Δ) follow Raymond et al. (2004), and be given by $a^{3/4}\Delta^{3/2}$. The surface density of our disk model, normalized to a density of 8.2 g/cm² at 1 AU, was assumed to follow an $r^{-1.5}$ profile, where r is the radial distance from the primary star. We also assumed that the water to mass ratios of embryos followed the current distribution of water in primitive asteroids of the asteroid belt (Abe et al. 2000). That is, embryos inside 2 AU were taken to be dry, the ones between 2 and 2.5 AU were considered to contain 1% water, and those beyond 2.5 AU were assumed to have water to mass ratios of 5% (Raymond et al. 2004).

We simulated the collisional growth of the planetary embryos of our binary-planetary system for 100 Myr, and for different values of the semimajor axis (a_b), orbital eccentricity (e_b), and mass of the secondary star. We followed Kasting, Whitmire, & Reynolds (1993), and considered a conservative habitable zone for the primary of our system at a distance between 0.9 AU and 1.5 AU from this star. Figure 1 shows the results of some of our simulations for an equal-mass binary with solar-type stars. As shown here, terrestrial-class planets with substantial amounts of water can form in the habitable zone of the primary star.

An important result obtained from our simulations was the relation between the binary perihelion (q_b) and the location of the outermost terrestrial planet (a_{out}). The left graph of figure 2 shows this for different simulations. As shown here, in simulations with no giant planet, similar to Quintana et al. (2007),

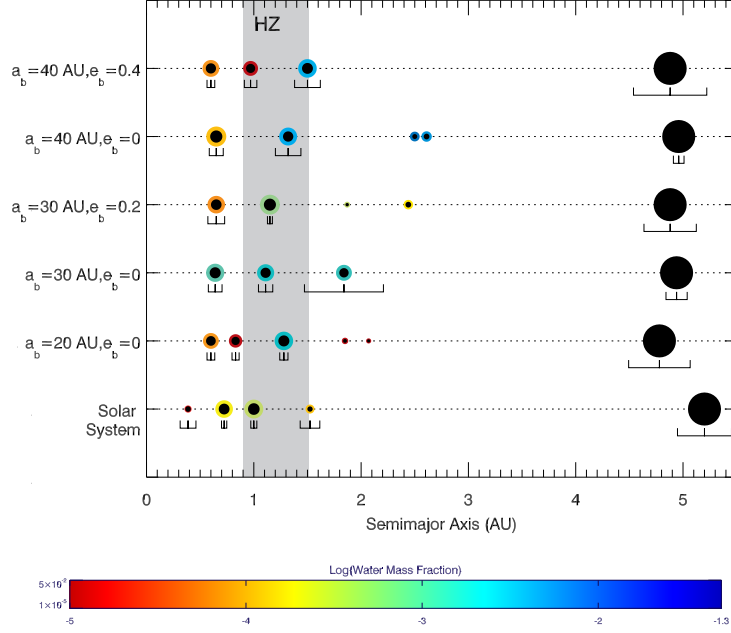


Figure 1. Formation of water-bearing terrestrial-class planets around the primary of a binary-planetary system with solar-mass stars. The big black circles represent the Jupiter-like planet of the system. Figure from Haghighipour & Raymond (2007).

terrestrial planet formation favors regions interior to $0.19q_b$. Given the location of the inner edge of the habitable zone (i.e., 0.9 AU), our simulations indicated that, in a binary-planetary system with a Sun-like primary, a stellar companion with a perihelion distance smaller than $0.9/0.19 = 4.7 \text{ AU} \sim 5 \text{ AU}$ may not allow Earth-like planets to form in the system's habitable zone. In simulations with giant planets, on the other hand, figure 2 shows that terrestrial planets form closer-in. The ratio a_{out}/q_b in these systems varies between 0.06 and 0.13.

A detailed analysis of the results of our simulations indicate that the systems, in which water-bearing planets were formed in their habitable zones, have relatively large perihelia. The right graph of figure 2 shows this for simulations in a binary with equal-mass Sun-like stars. The circles in this figure correspond to systems in which simulations resulted in the formation of habitable planets. The numbers on the top of the circles represent the mean eccentricity of the giant planet during the simulation. For comparison, the systems in which the giant planet is unstable have also been marked. Since at the beginning of each simulation, the orbit of the giant planet was considered to be circular, a non-zero eccentricity is indicative of the interaction of this body with the secondary star. As shown here, Earth-like objects are formed in systems where the average eccentricity of the giant planet is small. That is, in systems where the interaction between the giant planet and the secondary star has been weak. That implies, habitable planet formation is more favorable in binaries with moderate to large perihelia, and with giant planets on low eccentricity orbits.

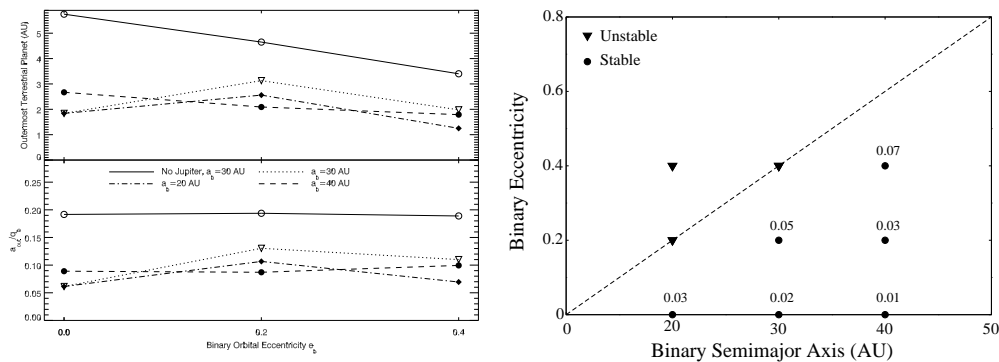


Figure 2. The graph on the left shows the relation between the perihelion of an equal-mass binary and the location of its outermost terrestrial planet. The graph on the right shows the region of the (e_b, a_b) space for a habitable binary-planetary system. Figures from Haghighipour & Raymond (2007).

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